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Study of early phase of current ramp-up in ITER with DINA code

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Introduction. Magnetic fields produced by the vacuum vessel and the charged poloidal field (PF) system complicate design of scenario of PF system operation during tokamak plasma initiation and complicate simulation of the plasma initiation. Due to low toroidal resistance of ITER vacuum vessel (VV), about 2 MA of eddy currents are induced in VV at breakdown which results in transient magnetic field in the plasma initiation region of about 30mT. At the same time the plasma current value after breakdown is about 100 times less than the VV one. In that case it is very complicated to provide the plasma position stabilization in the plasma initiation region with PF feedback control system, which is able to keep plasma after the plasma current is becoming 1.0 MA or more [1]. The plasma position after breakdown is extremely sensitive to the PF structure. A 0D analysis of PF coil scenarios of early phase of plasma current start up [2] does not provide a stable plasma behavior [3]. This paper presents the 2D simulation study results of the ITER plasma start up scenario with taken into account engineering design of the ITER PF system and the power supplies. These results include the free boundary ITER plasma equilibrium evolution together with energy and particle transport and performed with DINA code [4]. Simulations are starting from plasma current of about 60 kA after breakdown up to value about 600 kA.

Physical model. Presented simulations are carried out with use of 2D free–boundary equilibrium evolution solver and 1D poloidal flux diffusion on base of DINA code together with 0D balance equations approach following [2,5] for electrons and ions thermal energy:

$$\frac{3}{2}\cdot\frac{d(n_e T_e)}{dt} = P_{OH} + P_{ECRH} - P_{\Delta} - P_{ioniz} - P_{rad} - \frac{3}{2}\cdot\frac{n_e T_e}{\tau_E} \quad (1)$$

$$\frac{3}{2}\cdot\frac{d(n_i T_i)}{dt} = P_{\Delta} - P_{cx} - \frac{3}{2}\cdot\frac{n_i T_i}{\tau_E} \quad (2)$$

and particle balance for electrons n_e and neutrals n_0 respectively:

$$\frac{dn_e}{dt} = n_0 n_e S_i - \frac{n_e}{\tau_p} \quad (3) \qquad V_V \frac{dn_0}{dt} = \frac{n_0 V_p}{\tau_p} - n_0 n_e S_i V_p \quad (4)$$

In (1–4) the following notations are applied: V_p is the volume of plasma region, V_v represents the vacuum chamber volume, T_e and T_i are the electrons and ions temperatures respectively,

P_{OH} describes Ohmic heating specific power, P_Δ is the equilibration specific power between electrons and ions in plasma, P_{ioniz} is the neutral gas ionization specific losses, P_{cx} describes charge exchange specific losses, S_i is the particle source due to ionization, P_{rad} is the radiation power, P_{ECRH} is the ECR heating specific power, τ_E and τ_P are the energy and particles confinement times. The distribution of multi–electron ions n_z over ionization states is determined by the set of equations:

$$\frac{dn_z}{dt} = n_e\left(n_{z-1}I_{z-1} + n_{z+1}R_{z+1} - n_z\left(I_z + R_z\right)\right) + n_0 \cdot (n_{z+1}X_{z+1} - n_z X_z) - \frac{n_z}{\tau_{imp}} \qquad (5)$$

Here I_z and R_z are the ionization and recombination rates respectively, X_z is the charge–exchange rate. Ionization rate is supposed to be determined by electron impacts. The values of T_e and T_i from (1) and (2) equations are presented in the form of the plasma radial profile dependencies $T(\rho) = T_a(1-\rho^2) + T_b$, where T_b is assumed to be 10 eV, ρ is the label of magnetic surface. Carbon is considered as impurity in present simulations. The value of P_{ECRH} = 2 MW. Circuit equations for PFc and VV currents are used.

PF structure after breakdown. We start simulations when plasma current is assumed to be equal 60kA after breakdown. It is obvious that plasma equilibrium is an important problem during plasma current increase. Waveforms of PF coil currents are adjusted to provide the toroidal electrical field in the centre of breakdown region about 0.34 V/m, the vertical magnetic field in this region is about 5 mT and the radial magnetic field in this region is about 0.7 mT. Fig.1 shows the ITER plasma equilibrium with plasma current 60 kA after breakdown process, which is produced by PF coil currents presented in Table 1.

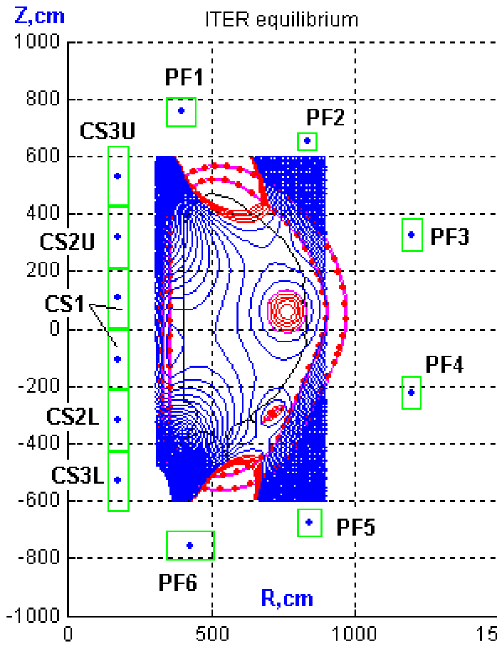

Fig.1 *ITER plasma equilibrium after breakdown process*

Table 1. PF coil current (MAt) after breakdown

CS3U	CS2U	CS1	CS2L	CS3L	PF1	PF2	PF3	PF4	PF5	PF6
20.9	18.4	19.8	20.7	18.0	9.6	0.17	0.21	0.09	0.2	8.3

Construction of the pre-programmed PF coil voltages and PF coil resistances for ITER start up scenario. For the analysis of the pre–programmed PF coil voltages the following model was used:

$$\frac{d(\mathrm{LI})}{dt} + \mathrm{R}_{\Omega}\mathrm{I} + \mathrm{M}_{p}\dot{\mathrm{I}}_{p} = \mathrm{U}, \qquad (6)$$

where L is the constant matrix of inductances all current circuits; I is the vector of currents in the circuits (PF coils and passive structure filaments); R_Ω is the diagonal matrix of the circuit resistances (for the circuits PF2 – PF5 the resistances are zero), M_p – vector of the constant mutual inductances of plasma with the circuits, $I_p(t)$ is the plasma current, which is taken from DINA simulations, U(t) is the vector of the pre-programmed voltages produced by the AC/DC converters. The goal of the study is to find the waveforms of the pre-programmed voltages and the values of the resistances for CSU3, CSU2, CS1, CSL2, CSL3, PF1, PF6 coils, which provide the necessary conditions for the plasma breakdown and ramp-up phase. The choice of the PF coil resistances should satisfy the present design of SNU (Switching Network Units) system [6]. One of the most important constraints imposed by SNU system is that the resistive voltages on this coils should be less than 8.5 kV. All PF coils are fed by AC/DC converters. Additionally, up to 1.5 kV are available from the main converters. At the currents less than 10 kA the PF2, PF3, PF4, PF5 coils may use the additional power supply with the voltage up to 4.2 kV from booster converter. Limits on the maximum PF coil currents and the magnetic field on the coil conductors were taken into account at the analysis, which are presented in Table 2. During plasma initiation, magnetic field on the conductors is limited by 13 T for all CS modules. Quadratic Programming method [7] with nonlinear constraints was applied to find the values of the PF coil resistances and the waveforms of the pre-programmed

Coil	I_{max}	B_{max}
CS3U	40 kA	13.0 T
CS2U	40 kA	13.0 T
CS1U	40 kA	13.0 T
CS1L	40 kA	13.0 T
CS2L	40 kA	13.0 T
CS3L	40 kA	13.0 T
PF1	48 kA	6.4 T
PF2	55 kA	4.8 T
PF3	55 kA	4.8 T
PF4	55 kA	4.8 T
PF5	52 kA	5.7 T
PF6	35 kA	6.8 T

Table 2. *Maximum CS and PF coil currents and magnetic field on the coils at the plasma initiation*

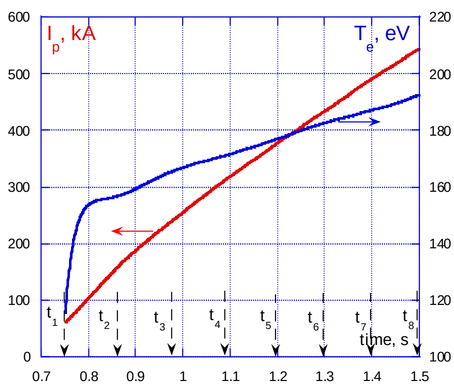

Fig. 2 *Evolution of plasma current and electron temperature during ITER plasma start-up*

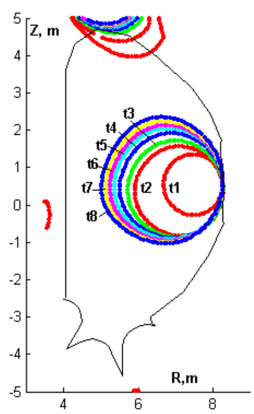

Fig. 3 *Plasma boundary evolution during ITER plasma start-up*

voltages in each time step. Obtained decision was iterated together with free boundary equilibrium. These waveforms were used in the 2D predictive simulations of ITER plasma start up with DINA code.

DINA predictive self-consistent simulation results of ITER plasma current start-up. With use of model described above we have obtained an ITER start up scenario starting from plasma current value of about 60 kA in t=0.75s up to about 600 kA in t=1.5s with obtained above pre-programmed PF coil voltages. In Fig. 2 the evolutions of plasma current I_p and electron temperature T_e during start-up are presented. In this figure the time moments are depicted, which correspond with plasma boundary evolutions shown in Fig. 3. Waveforms of currents in the coils with additional resistances (CSU3, CSU2, CS1, CSL2, CSL3, PF1, PF6) are presented in Fig. 4a and without ones (PF2, PF3, PF4, PF5) correspondingly in Fig. 4b. One can see that with use of constructed pre-programmed PF coil voltages and resistances we are obtaining the stable ITER plasma behavior during start up without PF feedback control.

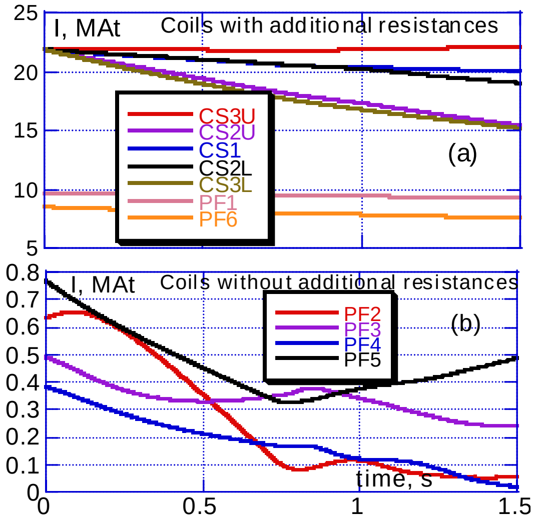

Fig. 4 *Waveforms of currents in the coils with additional resistances (a) and without ones (b)*

Conclusion. Method of pre-programmed construction of PF coil voltages and resistances together with 2D plasma equilibrium convergence iterations for ITER plasma start up operation is developed. ITER start up scenario from 60 kA up to 600 kA plasma current value is verified by means of 2D predictive DINA start up simulations.

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